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Plant height and internode length as components of lodging resistance in barley

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Abstract: With the total acreage of 50 million ha and an annual production of about 140 million tonnes, barley ranks high in world cereal production. Selection of new cultivars is mostly associated with a particular ideotype designed by the breeder in line with the targets and goals specified. Although grain yield is an ongoing objective in creating new cultivars, breeding work on barley is further expanded to include other traits, primarily grain quality and lodging resistance. Lodging resistance is largely determined by the genetic background of certain stem properties (length, strength and flexibility) and root system development i.e. structure. The degree of lodging resistance in barley is significantly affected by the morphological traits of aboveground parts (stem length, strength and flexibility; stem wall thickness; length, number and weight of internodes; spike size and spike weight). The new cultivars of winter malting barley currently used by producers are generally characterized by very good lodging resistance and an average plant height of 90 to 100 cm. Breeding spring malting barley has resulted in an optimal height (about 80 cm). Further changes should focus on increasing stem thickness and changing the anatomical structure to ensure sufficient stem strength.

Key words: barley, lodging, resistance, stem properties.

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Introduction

Cereals account for about 61% of total world arable land (Lef *et al*., 2004), with wheat occupying the largest area, followed by maize, rice and barley. In the first decade of the 21st century, barley was grown on 57 million ha of world land on average, with the total grain production of 140.8 million tonnes and an average grain yield of 2.6 tha^{-1} (Paunović *and* Madić 2011). Over the last years, the world barley production has shown a slightly decreasing tendency. During 2009-2013, the world area under barley cultivation was 49.8 million ha, with the total annual production of 137.3 million tonnes and an average yield of 2.75 t ha^{-1} *(FAOSTAT; average 2009-2013).*The poorer competitiveness of barley compared to that of wheat and maize has led to reductions in barley acreage in Serbia (except malting barley cultivars) to about 90,000 ha (Pržulj *et al.,* 2010). According to the Republic Bureau of Statistics data for the Republic of Serbia *(average: 2005-2015)*, barley is grown on 86,000 ha, with the total annual production of about 362,000 t and an average yield of 3.8 t ha^{-1}.

Barley breeding was initially mostly focused on increasing the grain yield potential which has remained one of the major breeding goals. Moreover, intense efforts have been made to increase lodging resistance (Pržulj *and* Momčilović, 2002; Madić *et al.,* 2009b; Pržulj *et al.*, 2010). In the 1980s and 1990s, breeding work was further expanded to include some other barley traits, primarily quality and resistance to biotic and abiotic limiting factors (Knežević *et al.,* 2007). The realization of the grain yield potential is dependent on a number of genetically determined factors and environmental conditions under which plants develop. The main components of yield, with the grain as its economic product, are number of plants per unit area, number of grains per plant and thousand-kernel weight. Maximum yield is the result of the most favourable balance between yield components (Paunović *et al.*, 2008 and 2009; Madić *et al.*, 2009b; 2012 and 2014).

Directed selection has resulted in the development of domestic cultivars of malting barley belonging to the continental ecotype, which produce grain of good malting properties even under such conditions. In the breeding programme, genotypes originating from eastern European countries have been used as donors of genes governing adaptability to semiarid conditions, and genotypes from western European countries have served as donors of genes that impart good quality (Pržulj *et al.,* 2010).

The objective of further breeding work is to create cultivars which have short strong flexible stem and exhibit tolerance to intensive production in high density stands. Plant height plays a very important role in grain yield formation, while being an important component of lodging resistance in barley. Plant height is largely determined by internode length, with the shortness of lower internodes ensuring greater lodging resistance. In addition to focusing on plant height reduction, Pržulj *and* Momčilović (1995) stressed that special attention in barley breeding work should be given to the anatomical structure to achieve sufficient stem strength. On the one hand, stem length reduction would be a desirable goal, given the marked susceptibility of barley to lodging. On the other hand, the positive correlations existing between stem length and grain yield require caution when selecting for stem length reduction as drastic shortening of the stem would lead to a significant decrease in total biomass and, hence, grain yield (Ore, 1991; Madić *et al.,* 2000 and 2005; Pržulj *et al.,* 2010, etc.).

Selection for lodging resistance

Lodging is a condition in which plants bend or lodge excessively or slightly during a particular developmental stage. This phenomenon is generally the result of plant's response to environmental mechanical effects (ecological factors and nutrient regime). Lodging resistance is a very important trait in barley as the least resistant species among small grain cereals. Damage due to lodging can be severe and, depending on plant developmental stage, it can cause high yield reductions, quality deterioration and harvesting problems. The most damaging effect of lodging is observed at flowering (heading). Lodging resistance is largely controlled by the genetic background of paricular stem properties (length, strength and flexibility) as well as by root system development i.e. structure. The morphological traits of the aboveground parts (stem length, strength and flexibility; stem wall thickness; length, number and weight of internodes; relationship between stem length and internodes; relationship between the root and the aboveground stem; leaf position and size; spike size and spike weight) have a significant effect on the degree of lodging resistance. Among these characteristics, the largest effect is produced by the length and strength of the first and second basal internodes (Madic *et al.,* 2009a and 2010). A more objective evaluation of lodging resistance can be made through analysis of the anatomical structure of the stem. Number of vascular bundles, thickness of the sclerenhymous tissue, number of rows of cells constituting the mechanical tissue layer, thickness of the parenchymal layer, diameter of the vascular system elements and stem wall thickness are positively correlated with lodging resistance (Pavlović, 1993). Plant height is directly associated with the degree of lodging resistance in barley. One of the goals of breeding is to reduce plant height i.e. create cultivars that have short, strong, flexible stems and exhibit tolerance to intensive cultivation in high density stands.

Quantitative properties, such as plant height among others, show continuous variability, with normal frequency distribution as the result of the effect of a number of genes. Plant height is also largely affected by environmental factors, and causes high variability in progeny, as suggested by Vasques *et al.* (1989).

In their study on stem length inheritance, Ceccarelli *and* Falcinelli (1978) found that longer stems are governed by dominant genes and that selection for reduced or increased plant height is analogously reflected in spike length.

According to the authors, this seems to result from bound genes or pleiotropic gene effects. They also determined that selection for longer stems results in an increased number of stem internodes, whereas selection for shortened stem does not cause considerable changes in internode numbers.

Table 1. Major agronomic traits of barley cultivars developed at the Small Grains Research Centre in Kragujevac (Madić *et al.* 2009b)

Cultivar	Length (cm)	Length of growing season	Lodging (rating 1-9*)	Yield (tha^{-1})	1 000 kernel weight (g)	% protein
Jagodinac	100	Medium early	3	7.2	45	11,0
Rekord	80	Medium early	2	7.6	39	11.9
Šampion	90	Medium early	1	7.1	48	12,0
Gigant	87	Medium early	2	7.4	43	13.1
Maksa	80	Medium early	1	7.8	42	11,0

** 1 - no lodging, 9 - 100% lodging*

Table 2. Major agronomic traits of barley cultivars developed at the Institute of Field and Vegetable Crops, Novi Sad (Pržulj *et al.* 2010)

Cultivar	Length (cm)	Length of growing season	Lodging (rating1-9*)	Yield (tha^{-1})	1 000 kernel weight (g)	% protein
Nonijus	96	Medium early	2	7.3	46	12.2
Ozren	79	Medium early	1	7.2	34	13.3
Javor	77	Medium early	2	7.3	36	14.6
Atlas	91	Medium early	2	8.1	35	12.5
Sremac	87	Medium early	2	7.7	39	13.0
Cer	100	Medium early	3	8.8	32	14.5
Rudnik	98	Medium early	2	7.8	39	14.4
NS525	90	Medium early	2	8.7	45	11.6
NS565	93	Medium early	1	8.6	43	10.6
NS583	89	Medium early	3	8.5	49	12.5
NS589	89	Medium early	3	8.6	50	12.3
NS593	90	Medium early	2	8.4	35	10.6
NS595	88	Medium early	2	8.5	38	10.7

** 1 - no lodging, 9 - 100% lodging*

Sears *et al.* (1981) and Thomas *et al.* (1984) found that four recessive genes control dwarf plant height. Mickelson *and* Rasmusson (1994) reported that short stature in barley is governed by one, two or three recessive genes, with the *sdw* gene wide-spread. The other two genes are contained in few genotypes and have not been defined yet. Hellewell *et al.* (2000) indicated that short stem and spike length in barley are determined by *sdw* and *denso* alleles mapped in the same region of the long arm of chromosome 3H and that the *sdw* allele reduced height by 10 to 20 cm. According to Pržulj *et al*. (2000), the genes that reduce stem length in barley have a different phenotypic effect compared to *Rht* genes in wheat (*dwarf* genotypes of barley have a very brittle stem).

After 25 years of research on dwarf barley genotypes, Mickelson *and* Rasmusson (1994) found that, compared to semi-dwarf genotypes, dwarf genotypes exhibit later maturity, higher susceptibility to diseases and poorer malt quality. New winter malting barley cultivars from Kragujevac and Novi Sad are characterized by very good resistance to lodging and an average plant height of 100 cm, indicating the potential for reduction in plant height by 10 to 20 cm in further breeding work (Tables 1 and 2). In breeding spring malting barley, an optimal height (about 80 cm) has been reached. Further selection should be focused on increasing stem thickness and changing the anatomical structure to ensure sufficient stem strength (Pržulj *and* Momčilović 1998).

Internode length is of large importance to plant height, with the priority given to the shortness of bottom internodes to increase stem strength and, hence, lodging resistance. Plant height can be reduced through the shortening of all internodes or the first and third internodes. An important factor that contributes to lodging resistance is the length of the second basal internode which is inherited through additive and dominant effects of genes in the F_1 and F_2 generations, with the non-additive effect being the most influential (Vazquez *and* Sanchez 1989; Knežević *et al.,* 1996; Madić *et al.,* 2010). Lodging resistance can also be increased by selecting genotypes that exhibit a vertical distribution of internodes that form a single axis, as opposed to non-resistant genotypes which have angles at internode junction points (Krivogornicyn *et al.* 1984).

All barley genotypes currently used by producers typically exhibit good resistance to lodging, which is, however, much lower than that of the most resistant wheat cultivars. One of the tasks of future breeding programmes for barley is to increase the degree of lodging resistance, which would enable the use of more intensive cultural practices, primarily larger amounts of mineral fertilizers

Conclusion

The new cultivars of winter malting barley currently used by producers are generally characterized by very good lodging resistance and an average plant height of 90 to 100 cm, suggesting the potential to reduce plant height by 10 to 20 cm in further breeding programmes. Breeding spring malting barley has resulted in an optimal height (about 80 cm). Further changes should focus on increasing stem thickness and changing the anatomical structure to ensure sufficient stem strength.

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VISINA STABLA I DUŽINA INTERNODIJA KAO KOMPONENTE OTPORNOSTI JEČMA PREMA POLEGANJU

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Rezime

Sa površinom od 50 miliona ha i godišnjom proizvodnjom od oko 140 miliona tona ječam zauzima značajno mesto u svetskoj proizvodnji žita. Selekcija novih sorti uglavnom je vezana za konkretan ideotip koji svaki oplemenjivač kreira prema potavljenim ciljevima. Iako prinos zrna ostaje konstantan cilj u stvaranju novih sorti, oplemenjivanje ječma se dalje proširuje i na druga svojstva, pre svega kvalitet zrna i otpornost prema poleganju. Otpornost prema poleganju je u najvećoj meri određena genetičkom osnovom određenih osobina stabla (visina, čvrstina i elastičnost) i razvijenošću odnosno građom korenovog sistema. Morfološke osobine nadzemnog dela kao što su visina, čvrstina, elastičnost i ispunjenost stabla, dužina, broj i težina internodija, veličina i masa klasa, značajno utiču na nivo otpornosti ječma prema poleganju. Nove sorte ozimog pivskog ječma koje su danas zastupljene u proizvodnji uglavnom se odlikuju vrlo dobrom otpornošću prema poleganju i prosečnom visinom stabla od 90 do 100 cm. Naredni programi oplemenjivanja imaju za cilj skraćenje visine stabla za 10 do 20 cm. U oplemenjivanju jarog pivarskog ječma postignuta je optimalna visina (oko 80 cm). Budući ciljevi su povećanje debljine stabla i promene u anatomskoj strukturi koje će stablu obezbediti dovoljnu čvrstinu.

Ključne reči: ječam, poleganje, otpornost, osobine stabla